

FUNDAMENTAL PHYSICS ON THE JEM-EF: THE LOW TEMPERATURE MICROGRAVITY PHYSICS EXPERIMENTS FACILITY

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The Low Temperature Microgravity Physics Experiments Facility (LTMPEF) takes advantage of the long-duration microgravity environment provided by the International Space Station and the payload accommodation of the Japanese Experiment Module's Exposed Facility (JEM-EF) to provide a NASA facility for fundamental physics research. Environmental factors influencing the quality of the experiments such as the vibration created within and by the Space Station, the charged-particle environment in low-Earth orbit, and the EMI environment will be discussed. Descriptions of the approved and candidate experiments will be presented as part of this presentation.

INTRODUCTION

The Low Temperature Microgravity Physics Experiments Facility (LTMPEF) offers Fundamental-Physics researchers within NASA's Office of Biological and Physical Research months of very stable low temperatures and small accelerations.

This paper addresses the experiment environment – what LTMPEF and the International Space Station (ISS) provide, as well as the environmental factors that may degrade the scientific return from the Facility.

Separate electronics boxes are used to control each experimental insert; a third box communicates with the ground through the Space Station, gathers data from the other two assemblies, and controls the dewar.

The Principal Investigators whose experiment proposals have passed peer review are responsible for developing their cryo-inserts and any associated unique hardware and software. Industrial partners are producing the reusable Facility: Ball Aerospace and Technologies Corporation, Design_Net Engineering, and Swales Aerospace. NASA's Jet Propulsion Laboratory provides project leadership as well as integration and operations support.

BACKGROUND

The LTMPEF Facility has evolved from Shuttle-based hardware that used a cryogenic dewar and inserts to study the physics of helium very close to the lambda point. An improved dewar design has significantly extended the on-orbit data-taking time.

The LTMPEF operates as an unpressurized payload on the International Space Station (ISS) and is attached to the Japanese Experiment Module's Exposed Facility (JEM-EF). The JEM-EF accommodates the mass (< 600 kg) and volume (~ 1.5 m³) required to house a dewar that can survive launch and last for months on orbit. The JEM-EF provides power and communication through the Payload Interface Unit or PIU. The vacuum of low-Earth orbit (~ 400 km) is used to pump on the dewar's Helium Tank to keep it cold.

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Low Temperature

The dewar provides a stable low temperature (at or below 1.6 K) over 4 to 5 months. Its Helium Tank is insulated from the temperature variations of the external Facility and the Vacuum Shell; the helium will be stable to better than the required ± 50 mK.

The vacuum of space pumps on the helium bath through a phase separator that contains the liquid. The heat flowing into the helium (from an experiment or through the dewar) and the impedance of the plumbing and phase separator are factors in the ultimate temperature of the helium; modeling predicts it will be below 1.6K – a significant fraction of the liquid will be in the superfluid state. The 180 liters of superfluid helium provide a large thermal sink and its large thermal conductivity aids in maintaining stable thermal environments at the instrument interfaces.

The science cells are mounted on a thermo-mechanical structure with resistive truss elements supporting conductive stages with large thermal heat capacities (see Figure 1). The thermal truss/stage structure combined with Germanium Resistance Thermometers (GRTs) and heaters provide increasingly reduced levels of thermal noise: from the mK of the helium bath to μ K.

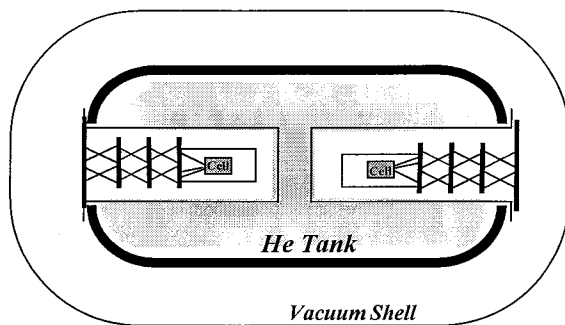


Figure 1. Cartoon of LTMPEF dewar containing two inserts.

After two stages a GRT can no longer provide a meaningful error signal to the servo controller. For these and higher levels of thermal control paramagnetic-salt thermometers are used in conjunction with Superconducting Quantum Interference Devices (SQUIDs) to detect smaller temperature differences: to better than 1 nK. More precise 4-wire heaters are used for this level of control.

To further ensure low levels of thermal noise the space around the science cell is evacuated to eliminate conduction and cold radiation shields are used to limit radiation.

The net result is a very stable thermal environment in which a small amount of helium can be studied or a temperature-sensitive device can be operated.

Location	Temp.	Stability
LTMPEF Exterior	-9C (264K)	37 K
Dewar Vacuum Shell	-21C (252 K)	16 K
Helium Tank	1.6 K	50 mK
Truss Stage #1	2.0 K	50 μ K
Truss Stage #2	2.16 K	50 nK
Sample Cell	2.17 \pm nK	< 1nK

Table 1. Typical Temperatures in the LTMPEF.

Microgravity

In concert with the quiet thermal environment, the ISS orbit creates a reduced-gravity condition; the resulting accelerations are measured in micro-gees (μ g) in comparison to Earth's one-gee field. The dc acceleration is the result of several factors: the rotation of the Earth-centered ISS, atmospheric drag, and gravity-gradient effects. The latter depends on an object's location relative to the ISS's center of mass: LTMPEF is roughly 18 m away (see Figure 2). The greatly reduced levels permit the study of

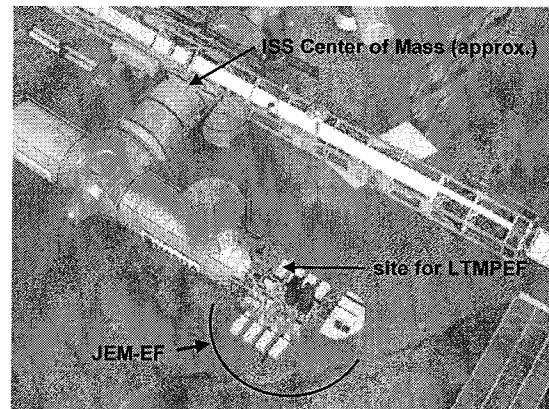


Figure 2. The ISS location (JEM-EF site #2) where LTMPEF will be located for its first flight..

systems that would tend to stratify under gravitational forces.

The LTMPF dewar and its controls plus the ISS and its orbit provide the ingredients to create a very simple, controlled thermodynamic environment for the sample fluid. The scientists perturb this equilibrium and monitor the sample's response to learn more about the fundamental laws of physics.

CANDIDATE EXPERIMENTS

DYNAMX

The Critical Dynamics in Microgravity Experiment (or DYNAMX) looks at the behavior of the two components of helium (normal and superfluid) under a very small heat flow. The experimental results address dynamic behavior at a phase transition. Starting with a cell completely in the superfluid state, heat is steadily added to one end of the cell, it raises the temperature of the helium and causes a small portion of the helium to become a normal fluid. By unfolding the temperature as a function of time at three locations in the sidewall, the Principal Investigator, Professor Rob Duncan of the University of New Mexico, will be able to determine the thermal conductivity of liquid helium very close to the lambda point.¹

CQ

A second experiment, the Heat Capacity of Superfluid He-4 in the Presence of a Heat Flux (or CQ), measures heat capacity to investigate the onset of normal-fluid behavior; this temperature is known as $T_C(Q)$. CQ will be performed using the same hardware as DYNAMX; it too uses small heat fluxes to create a non-equilibrium system. PI Professor David Goodstein of Caltech will use measurements of the heat capacity as a function of temperature and heat flux to understand the transition temperature and to confirm ground observations of enhanced heat capacity.²

MISTE

The liquid-vapor phase transition of helium-3 is used in the Microgravity Scaling Theory Experiment (MISTE) to obtain precision measurements of the specific heat, C_V , and the isothermal compressibility, k_T , as the phase diagram is scanned over temperature at a constant density and over density at a constant temperature. PI Martin Barmatz of JPL will use these data to determine critical exponents and amplitude ratios to test the scaling laws relating

these exponents. Equations of state for the helium-3 system can be compared using MISTE's simultaneous measurements of the pressure, temperature, and density.³

COEX

Using the MISTE hardware the Coexistence Experiment (COEX) will detect the coexistence curve of the helium-3 system. Starting at a temperature above the ^3He critical point (3.31K) and a fixed density, the temperature of the cell will be reduced. PI Inseob Hahn of JPL will use the abrupt change in specific heat (or rate of cooling) to obtain a single point on the coexistence curve.

BEST

Using three cells with one or more small dimensions the Boundary Effects on the Superfluid Transition (BEST) Experiment studies the effects of applying heat to the "confined" liquid helium. In one cell the helium is confined in cylindrical capillaries; in another cell pancake-shaped volumes are studied. The pressure in the cells can be varied over a large range. One end of the samples will be heated; high-resolution thermometers will measure the temperature at the other end. PIs Professor Guenter Ahlers of UCSB and Feng-Chuan Liu at JPL will use this thermal conductivity information to understand molecular dynamics and cross-over behavior as the number of dimensions changes from three to two or three to one.⁴

SUMO

The Superconducting Microwave Oscillator (SUMO) Experiment uses the low temperature of the LTMPF's dewar as an intermediate thermal stage so it can maintain a superconducting microwave-cavity-stabilized oscillator system at roughly 1 K. SUMO can be used for relativity or clock experiments by itself. It can also be operated simultaneously with other types of clocks on the ISS as they move through the changing gravitational potential over the Space Station's orbit or for comparison with other clocks on the ground. SUMO can be used as a local oscillator for experiments with cold-atom clocks.⁵

DYNAMX and MISTE are the principal experiments to be conducted on the first mission of LTMPF, M1, scheduled to launch in the fall of 2005. CQ and COEX will also be operated on M1 if they successfully complete their Science-Concept and Requirements-Definition Reviews. BEST and SUMO have completed their SCRs and, if successful

at their RDRs, they will fly on the second flight of the LTMPEF Facility, M2.

SENSITIVITY TO THE ENVIRONMENT

DC Acceleration

One of the requirements for the acceptance of experiments to fly in the LTMPEF is that they require the ISS orbit – either for its microgravity and/or its varying gravitational potential. The sensitivity to acceleration varies from experiment to experiment but all benefit from the lowest possible residual dc acceleration, cannot collect their primary science data during ISS maneuvers, and experience ISS vibrations and transients as a noise source.

The residual dc acceleration sets a bottom limit on the quality of an experiment. At site 2 on the JEM-EF, the average value of the dc acceleration is $2.7 \mu g_{rms}$. The residual acceleration limits the uniformity of conditions within the sample cell; for example it creates a small density gradient within a fluid system. This is the case with the MISTE experiment. As a result the science team for MISTE is considering orienting their cell so that its axis of symmetry is aligned with the projected residual acceleration. Designs that are less sensitive to the relative orientation of the acceleration provide less sensitive measurements.

The variation over an orbit of the dc acceleration at the LTMPEF attachment to the JEM-EF is shown in Figure 3.

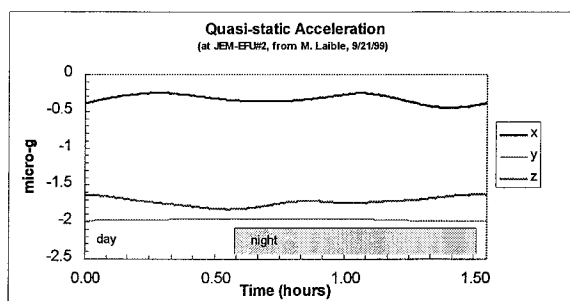


Figure 3. Variations in dc acceleration over an orbit (in ISS coordinates).⁶

In contrast DYNAMX is not very sensitive to the dc acceleration. It is more susceptible to vibrations in support structures or its sensors that could create heating near the science cell. This heat is the end

product of energy injected into the system as mechanical vibration (i.e., damping).

Originally it was believed that LTMPEF would have to incorporate a vibration-isolation mechanism to reduce vibrations. Analysis by the DNMAX and other LTMPE PIs, indicates that there is some margin between their requirements and the estimated vibration levels at EFU#2 as provided by both Space Station and JEM-EF modeling (see Figure 4). To further protect themselves the DYNAMX team has designed the components in proximity to the sample to be very light in weight. In addition the Facility has been designed so that there is a separation between the fundamental frequencies of the Dewar, the Inserts, and the cells; this should act as a multi-pole low-pass filter to attenuate the higher-frequency vibrations.

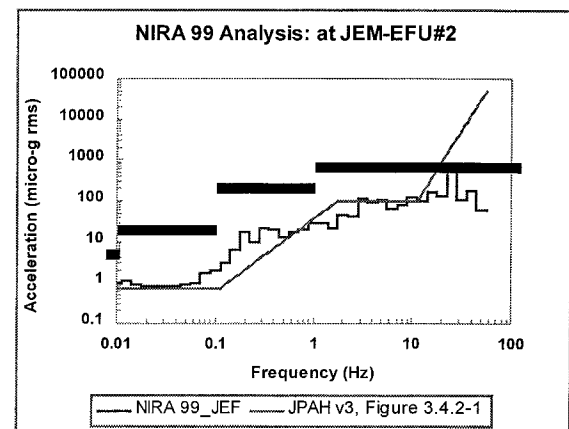


Figure 4. The broad lines show the maximum vibrations levels under which LTMPE experiments can operate.⁷ The NIRA analysis is a product of the ISS Microgravity Analysis and Integration Team.⁸ The JPAH data is the environment that the JEM-EF will provide to EF payloads.⁹

To quantify the impact that the actual external acceleration environment has on a particular data measurement or experiment run, LTMPEF will have a triaxial accelerometer mounted within the system; it will be provided by the Space Acceleration Measurement System (SAMS) Project of NASA Glenn Research Center. LTMPEF PIs will be able to determine if there is a correlation between any anomalous science measurements and the acceleration data.

Magnetic Fields

The transformer common to all of LTMPEF's high-resolution measurements is the Super-conducting Quantum Interference Device (SQUID); it is an

extremely sensitive magnetometer over a very large dynamic range. The impact of additional unwanted magnetic flux within the measurement system, or of currents that appear to be such, strikes at the heart of the integrity of the instrumentation system.

The ISS passes through the Earth's magnetic field in its orbit creating a slowly varying field. Other ISS payloads and systems also can generate magnetic disturbances.

Each of the twelve SQUID sensors is completely enclosed in a niobium-titanium housing which is a super-conductor at the Insert operating temperatures. The wires that couple the SQUIDs to their transducers and connect them to their electronic controllers are also shielded with superconducting materials. The superconducting material acts to repel magnetic fields, thereby isolating the SQUID sensor, its input pickup, and its output from their surroundings; regular conductors shield the output wires at higher temperatures as they go to the controller electronics.

There are situations where the PIs need high magnetic flux densities. In these cases they use superconducting niobium tubes and external magnetic field generators to trap magnetic flux for the duration of the time that the system is cold. The external coils are turned off after the field has been trapped in the "flux tubes."

An additional high-permeability magnetic shield surrounds the exterior of each of the two Cryo-Inserts; this Cryotherm is specially designed to trap field lines at low temperatures.

Charged Particles

For experiments trying to control and/or measure very small heats (a few pW), like DYNAMX and CQ, the energy deposited when a charged particle interacts with the electrons in the paramagnetic salt or sample cell will cause an apparent increase in temperature. At low latitudes the Galactic Cosmic Rays (GCRs) can deposit 0.5 to 15 pW/gram. Inside the South Atlantic Anomaly (SAA, where the van Allen radiation belt is nearest the Earth's surface) trapped particles cause heating on the order of 500 pW/gram. This is enough energy that DYNAMX plans to put its cell into a low-temperature superfluid state during SAA traversals. Professor Steve Boyd has estimated what the charged particle environment might be for the first mission of LTMPEF; Figure 5 is an early result.¹⁰

As the energy is proportional to the mass of the material, the designers of DYNAMX have made the thermometers, the sample-cell assembly (which contains a bubble chamber and cell-fill valve), and its support structure as lightweight as possible. The thermometers attached to the cell are sampled fast enough to discriminate individual strikes on the thermometric elements. Interactions elsewhere add to the noise background; at higher latitudes measurements may be suspended due to the increase in background noise.

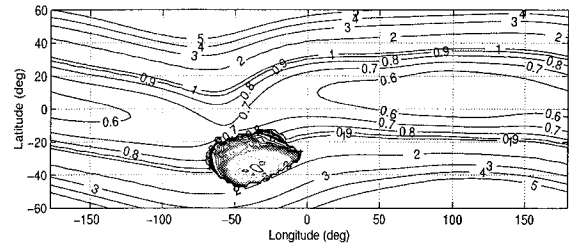


Figure 5. Estimated charged-particle heating in 2005.

No shielding of the science hardware from charged particles has been included in the Facility design. Measurements made using similar sensitive experiments on the Space Shuttle indicate that attempting to shield the system would just create secondaries that end up depositing more energy.

A charged-particle dosimeter system that flew on the earlier STS missions will be reflown in LTMPEF to monitor charged particles.

Electromagnetic Interference

One of the most difficult sources of noise to track down and isolate in any high-resolution measurement system is that generated by electromagnetic interference. Given the pervasive presence of EM energy on the ground, LTMPEF researchers as well as space-instrument developers have over years learned techniques to reduce the generation of such noise and to attenuate those signals that are generated externally. The ISS itself has many sources of EM energy: internally generated conducted emissions, dc-to-dc converters, leakage from radiated communications signals, and the bathing of EM signals from Earth-bound antennae.

The ISS has requirements and recommendations on how to design hardware that is to be operated on

Station. LTMPEF has followed these recommendations; our engineers realize that that will not be enough. The Vacuum Can that is the first structure outside the science cell is a multi-piece aluminum shield; the Helium Tank also adds attenuation, as does the dewar's external Vacuum Shell. The edges of the Vacuum Shell are all treated to enhance their conductivity when assembled. The wiring inside the dewar has a variety of shields and grounds to minimize the cross talk between LTMPEF signals. Outside the Dewar all wiring is encased in some form of conductive conduit. Finally the LTMPEF secondary structure is a set of aluminum honeycomb panels; by making all of its seams conductive with overlaps and minimizing any apertures it becomes the Facility's outermost Faraday cage that is bonded to the ISS structure.

Internally power conditioning is done on each board; each board has a single-point ground for all of its signals.

CONCLUSION

It is important for the design of experiment hardware to understand the range of environmental conditions that a system is likely to experience on orbit. It is equally important to confirm that understanding with actual measurements. Correlating sources of possible degradation with actual data confirms our understanding of the systematic effects that can then be eliminated operationally or by post-processing of the data.

¹ Day, P. K., W. A. Moeur, S. S. McCready, D. A. Sergatskov, F.-C. Liu, and R. V. Duncan, Phys. Rev. Lett., **81**, 2474, (1988).

² Harter, A. W., R. A. M. Lee, A. Chatro, X. Wu, T. C. P. Chui, D. L. Goodstein, Phys. Rev. Lett., **84**, 2195, (2000).

³ Hahn, I., F. Zhong, M. Barmatz, R. Haussmann, J. Rudnick, Phys. Rev. Lett. E, **63**, 055104 (2001).

⁴ G. Ahlers, P. Finley, E. Genio, K. Kuehn, F. Liu, Y. Liu, S. Mehta, and D. Murphy 'Boundary Effects near the Superfluid Transition (BEST), an Experiment Proposed for the ISS.' in CP504, Space Technology and Applications International Forum - 2000, edited by M.S. El-Genk (American Institute of Physics, 2000), p. 662.

⁵ Nissen, J. A., J. A. Lipa, S. Wang, D. Avaloff, D. A. Stricker, S. Buchman, 2nd Pan Pacific Basin Workshop on Microgravity Sciences, **Paper FP-1033**, (2001).

⁶ M. Laible, private communication, 9/22/99.

⁷ F. C. Liu, M. J. Adriaans, M. Larson, LTMPE Science Requirements Envelope Document, JPL D-16322, rev. A, (2001).

⁸ Thampi, S., Non-Isolated Rack Assessment (NIRA 99), Microgravity Mode, presentation to ISS Microgravity Analysis and Integration Team, (August, 1999).

⁹ Japanese Experiment Module (JEM) Payload Accommodation Handbook, volume 3, NASDA-ESPC-2563, (Dec. 2000).

¹⁰ Boyd, S. T. P., W. Holmes, R. V. Duncan, presentation at Microgravity Fundamental Physics Workshop, April 28- May 1, 1999, see also http://coffee.phys.unm.edu/~stpboyd/space_environment/index.html